

Technical Note

Thermodynamic analysis of a Stirling engine including regenerator dead volume

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ARTICLE INFO

Article history:

Received 10 March 2010

Accepted 18 July 2010

Available online 14 August 2010

Keywords:

Stirling engine

Regenerator

Imperfection

ABSTRACT

This paper provides a theoretical investigation on the thermodynamic analysis of a Stirling engine with linear and sinusoidal variations of the volume. The regenerator in a Stirling engine is an internal heat exchanger allowing to reach high efficiency. We used an isothermal model to analyse the net work and the heat stored in the regenerator during a complete cycle. We show that the engine efficiency with perfect regeneration doesn't depend on the regenerator dead volume but this dead volume strongly amplifies the imperfect regeneration effect. An analytical expression to estimate the improvement due to the regenerator has been proposed including the combined effects of dead volume and imperfect regeneration. This could be used at the very preliminary stage of the engine design process.

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1. Introduction

The Stirling engine was invented in 1816 by Robert Stirling [1]. The first era of the Stirling engine was ended by the rapid development of internal-combustion engine and the electric motor. The second era began around 1937 [2]. A wide range of investigations has been made on the development of Stirling engine [3] but further developments are still needed for wider practice applications [4–6]. Its application has several advantages like multi-fuel capability, low fuel consumption and low noise [3]. The variety of fuel sources (gases or liquids) and abundant heat sources (solar radiation [7]) that can be used are of particular interest. The current applications under development are heating and cooling, combined heat and power, solar power generation, Stirling cryocoolers, heat pump, marine engines, nuclear power generation, automotive engines, electric vehicles, aircraft engines and low temperature difference engines. Commercial Dish-Stirling system of 25 kW [8] takes the energy from the sun and converts it into electrical energy providing a clean, efficient and reliable source of energy. Micro systems are of primary importance in the latest development. Demonstration models have been realized like commercial Low Temperature Difference Stirling Engines running on any warm surface (i.e., a cup of hot water) [9]. Reduction in the dimensions can lead to new designs. The moving component could be replaced by vibrating membranes as in the miniaturized membrane engine [10].

Despite the apparent conceptual simplicity of the Stirling engine, the mathematical analysis is complicated. The first analysis

of a Stirling engine was published by Schmidt in 1871 [11] and has been reported in a more comprehensive form in the book of Urieli and Berchowitz [12]. For all new designs, a simple thermodynamic analysis is performed even in the case of recent development to determine the characteristics [13]. As efforts to reduce some loss mechanisms could tend to aggravate others, complementary approaches are needed. A simple model could be used at the first stage followed by a sophisticated approach including computation could be necessary. It is noted that a practical Stirling cycle always departs significantly from the ideal cycle mainly due to the performance of the heat exchanger and the regenerator. Some detailed analysis with practical values and examples of the engine are given by Organ [14]. The commercially available codes, as CFD-ACE and Fluent, provide a macroscopic porous-media model where permeability, inertial coefficient, and porosity are required as the input parameters. Pressure drop and temperature profile are obtained with accuracy [15] and could be used to improve the existing system [16]. Anyway, a simple mathematical model calculation is of primary importance to understand in depth the parameters that need to be optimized.

Several forms of cylinder coupling in Stirling engine can be used, but the more common is the opposed-piston configuration known as alpha configuration with sinusoidal volume variation of working space [3].

Here we consider a model system of practical importance consisting of a notional discontinuous piston motion and a simple harmonic piston motion. This work could be used in the understanding of an imperfect regenerator and the dead volume coupled effects in the primary stage of an engine design. It is a complementary work of Kongtragool and Wongwises [17] who have associated the heat of the hot isothermal expansion, a part of the

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Nomenclature

A	surface section of the regenerator
C_V	specific heat at constant volume
$C_{V,m}$	molar specific heat at constant volume
e	thermal efficiency
γ	ratio of the specific heat at constant pressure to constant volume
L	length of the regenerator
n	mole number
n_h	mole number in the heater
n_k	mole number in the cooler
n_r	mole number in the regenerator
p	absolute pressure
Q_h	heat furnished by the heater
Q_k	heat furnished by the cooler
$Q_{r,1 \rightarrow 3}$	heat released by the regenerator
R	gas constant
U	internal energy

θ	cycle angle varying between 0 to 2π
T	temperature
T_h	heater temperature
T_k	cooler temperature
T_r	regenerator temperature
V	volume
V_h	heater volume
V_k	cooler volume
V_m	minimum volume considering V_h and V_k only
V_M	maximum volume considering V_h and V_k only
V_r	regenerator volume
W	work
W_h	work for the heater piston
W_k	work for the cooler piston
W_t	engine net work
x	fraction of the heat furnished by the heater and released by the regenerator
z	linear abscissa

cycle, to the heat supplied externally in order to explore the combination of dead volume and imperfect regeneration effects. However, the mole variation in the regenerator during isothermal transformations has not been properly taken into account. In this article, we have carefully analysed the combination of dead volume and imperfect regeneration particularly the effect to the heat stored in the regenerator and the mole number in each of the three volumes (heater, cooler and regenerator) that enables us to understand the variation of efficiency in these cases. With this simple approach, we compare the heat stored and the heat rejected by the regenerator with the net work. This allows us to determine an analytical expression that takes into account the dead volume and the imperfect regeneration.

2. Stirling cycle analysis

The Stirling cycle based on two opposing pistons in motion is shown in Fig. 1. It consists of two isothermal and two isochoric processes (Fig. 2). During the isothermal compression (1–2), the cold piston moves towards the regenerator. In the following step (2–3), both pistons move similarly so that the volume remains constant and the working fluid is transferred through the regenerator. This step is followed by the isothermal expansion process (3–4) with only the hot piston moving. In the step (4–1) both pistons move keeping the volume constant and transferring the

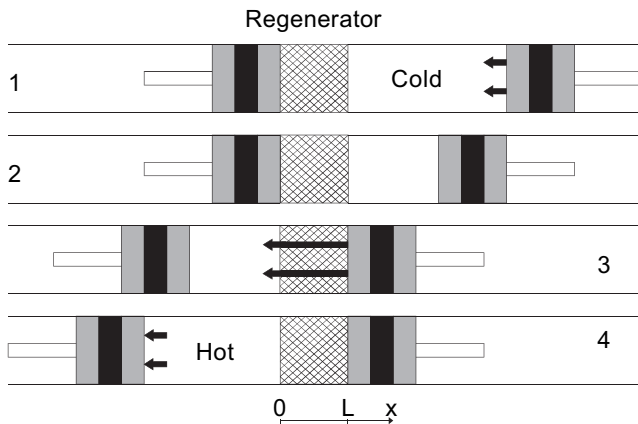


Fig. 1. Piston positions.

working fluid through the regenerator. This is an ideal cycle assuming the perfect heat transfer and does not take into account heat losses during the regeneration. First we consider an ideal case of perfect gas with infinite conductivity for all materials. Therefore, we have:

$$dU = C_V dT = nC_{V,m} dT, \quad \delta W = -pdV \quad \text{and} \quad \delta Q = dU - \delta W$$

2.1. Regenerator temperature

Within the isothermal hypothesis, the temperature should vary continuously between the cold (T_k) and the hot space (T_h). Irreversible processes take place if a temperature difference exists between the thermostat and the gas. Here, the gas temperature is always at the thermostat temperature, leading to no creation of entropy. Experimentally, for homogeneous regeneration, a linear variation of the temperature versus the position has been observed [12]. Considering that the temperature varies linearly from T_k at the abscissa 0 to T_h at the abscissa L , the mole number $n_r(z)$ in the volume Adz at the abscissa z is:

$$n_r(z) = \frac{pAdz}{R(T_h + \frac{z}{L}(T_k - T_h))}$$

In the regenerator volume $V = AL$, n_r is

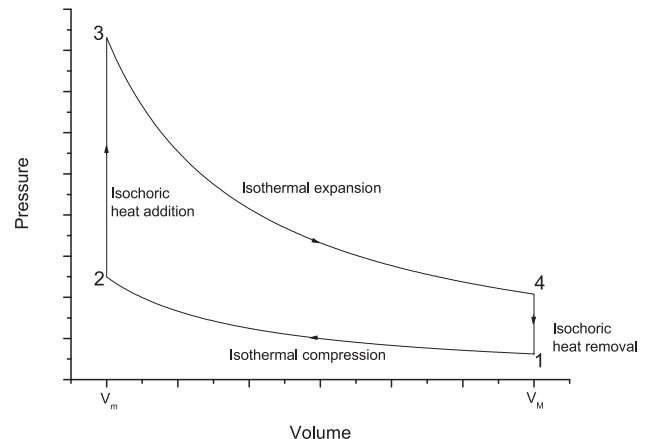


Fig. 2. Watt Stirling cycle with notional discontinuous piston motion.

$$n_r = \int_0^L n_r(z) = \frac{pV}{RT_r} \quad \text{with} \quad T_r = \frac{T_h - T_k}{\ln\left(\frac{T_h}{T_k}\right)}.$$

Consequently, we can use the regenerator temperature for all mechanical calculations, i.e., to determine pressure. If the hot and the cold space are at the same temperature, the divergence in the expression can be avoided by adding an incremental value to one of the temperatures. For heat exchange, with no dead volume, all molecules go through the regenerator and receive an amount of heat dependent only on $T_h - T_k$ and the regenerator temperature has no effect. Nevertheless, the direction of the heat flow is dictated by the second law of thermodynamics.

3. Notional discontinuous piston motion

3.1. Without regenerator dead volume and with perfect regeneration

In the simplest case without dead volume and with perfect regeneration, all quantities can be easily calculated (Table 1).

During the isochore transformation, the pressure is given by

$$p = \frac{nR}{\frac{V_h}{T_h} + \frac{V_k}{T_k}}$$

So, we can calculate the work $W_h = \int p dV_h$ and $W_k = \int p dV_k$ which are opposite in sign to each other (see Table 2)

The Carnot efficiency is reached according to:

$$e = -\frac{W_t}{Q_h} = 1 - \frac{T_k}{T_h} \quad \text{with} \quad W_t = W_h + W_k$$

$$= -nR(T_h - T_k) \ln\left(\frac{V_M}{V_m}\right)$$

where W_t is the net work and e the efficiency.

3.2. With regenerator dead volume and with perfect regeneration

In this case, the mole number is given by:

$$n = n_k + n_r + n_h,$$

the pressure by

$$p = \frac{n}{\frac{V_k}{RT_k} + \frac{V_r}{RT_r} + \frac{V_h}{RT_h}},$$

and the internal energy by

$$U = \frac{R}{\gamma - 1}(n_k T_k + n_r T_r + n_h T_h) \quad \text{with} \quad \gamma = \frac{C_p}{C_v}$$

The piston work can be calculated and is presented in Table 3.

Table 1
Energy quantities without dead volume.

Transition	Work W	Heat Q	ΔU
1→2	$-nRT_k \ln\left(\frac{V_m}{V_M}\right)$	$nRT_k \ln\left(\frac{V_m}{V_M}\right)$	0
2→3	0	$nC_{V,m}(T_h - T_k)$	$nC_{V,m}(T_h - T_k)$
3→4	$-nRT_k \ln\left(\frac{V_M}{V_m}\right)$	$nRT_k \ln\left(\frac{V_M}{V_m}\right)$	0
4→1	0	$nC_{V,m}(T_k - T_h)$	$nC_{V,m}(T_k - T_h)$

Table 2

Work for cold and hot space without dead volume. The work for a transition is simply $W = W_h + W_k$.

Transition	Work hot space W_h	Work cold space W_k
1→2	0	$-nRT_k \ln\left(\frac{V_m}{V_M}\right)$
2→3	$-nR \frac{T_k T_h}{T_r}$	$nR \frac{T_k T_h}{T_r}$
3→4	$-nRT_h \ln\left(\frac{V_M}{V_m}\right)$	0
4→1	$nR \frac{T_k T_h}{T_r}$	$-nR \frac{T_k T_h}{T_r}$

To determine the heat transferred by the hot space, the isothermal transition 3→4 cannot be used as the mole number in the regenerator is not identical at position 3 and position 4. However the cyclic change in the number of moles of the working gas has to be zero for each of the cells. Thus, integrating over the cycle, we obtain for the working spaces:

$$Q_k = -W_k, \quad Q_h = -W_h \quad \text{and} \quad Q_r = 0$$

For the ideal regenerator $Q_r = 0$ because all heat exchange between the regenerator matrix and the working gas is internal. A first order development of the net work versus the regenerator dead volume gives:

$$W_t = -nR(T_h - T_k) \left[\ln\left(\frac{V_M}{V_m}\right) - V_r \frac{T_h + T_k}{T_r} \left(\frac{1}{V_m} - \frac{1}{V_M} \right) \right]$$

It is observed that the net work is reduced.

At the same time, the thermal efficiency equals the Carnot efficiency

$$e = -\frac{W_t}{Q_h} = \frac{W_{h,34} + W_{k,12}}{W_{h,12} + W_{h,23} + W_{h,34}} = 1 - \frac{T_k}{T_h}$$

So, we can conclude that the dead volume has no influence on the efficiency in the ideal case, that contradicts to the results obtained by Kongtragool and Wongwises [17] where a decrease of the efficiency is found with increasing dead volume. The disagreement comes from the simplifications used by Kongtragool and Wongwises. Contrary to our approach, the authors [17] consider a constant mole number in the regenerator during the isothermal expansion.

3.3. Without regenerator dead volume and with imperfect regeneration

Taking into account all the conclusions from the previous subsection, one can write the added heat as:

$$Q_{r,1 \rightarrow 3} = U_3 - U_2 = nC_{V,m}(T_h - T_k) = n \frac{R}{\gamma - 1}(T_h - T_k)$$

Table 3

Work for cold and hot spaces with dead volume.

Transition	Work hot space W_h	Work cold space W_k
1→2	0	$-nRT_k \ln\left(\frac{V_r + V_m}{V_r + V_k}\right)$
2→3	$-nR \frac{1}{T_k - T_k} \ln\left(\frac{V_r + V_m}{V_r + V_h}\right)$	$nR \frac{1}{T_k - T_k} \ln\left(\frac{V_r + V_m}{V_r + V_h}\right)$
3→4	$-nRT_h \ln\left(\frac{V_r + V_M}{V_r + V_h}\right)$	0
4→1	$-nR \frac{1}{T_h - T_k} \ln\left(\frac{V_r + V_M}{V_r + V_h}\right)$	$nR \frac{1}{T_h - T_k} \ln\left(\frac{V_r + V_M}{V_r + V_h}\right)$

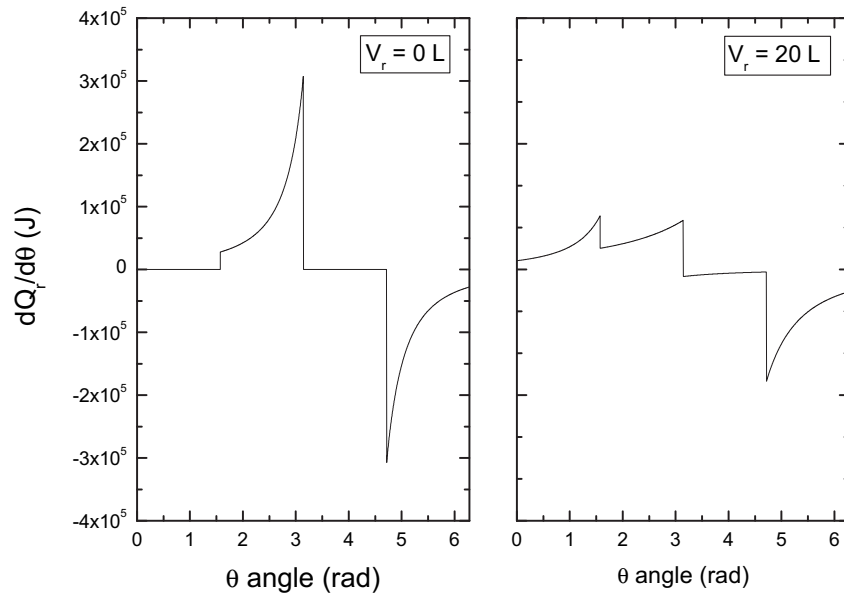


Fig. 3. Heat exchange in the regenerator.

If x is the fraction of the external heat transferred to the regenerator when the gas is heated, we should add this heat to the total heat input to the system

$$Q_{\text{input}} = xQ_{r,1 \rightarrow 3} + Q_h$$

leading to an efficiency of

$$e = -\frac{W_t}{Q_{\text{input}}} = \left(1 - \frac{T_k}{T_h}\right) \left(\frac{1}{1 + \frac{x}{\gamma - 1} \frac{1 - \frac{T_k}{T_h}}{\ln\left(\frac{V_M}{V_m}\right)}} \right)$$

3.4. With regenerator dead volume and with imperfect regeneration

In order to investigate this case numerical simulations are needed. The energy released and stored by the regenerator is calculated using $V_m = 10$ L, $V_M = 40$ L, $R = 8, 31$, $\gamma = 1.4$, $n = 10$ mol, $T_k = 300$ K, $T_h = 1000$ K. The regenerator volume is indicated in the graphs in which the regenerator heat variation is plotted versus the angle θ (see Fig. 3).

For the 3 spaces, we can calculate the variation of the internal energy ($dU = nC_{V,m}dT$), the elementary work $\delta W = -pdV$, and the elementary heat as follows:

- in the hot and cold space:

$$\delta Q = dU - \delta W,$$

- in the regenerator space:

$$\delta Q_r = dU_r + dn_{k \rightarrow r} C_{V,m}(T_r - T_k) + dn_{h \rightarrow r} C_{V,m}(T_h - T_r)$$

For $V_r = 0$, we obtain $Q_r = nC_{V,m}(T_h - T_k) = 145.4$ kJ which is the area corresponding to the $2 \rightarrow 3$ transformation.

With the example reported in Table 4, we clearly see that the heat exchange in the regenerator is nearly the same while the net work is strongly reduced. So the association of both these effects leads to a decrease in the efficiency and the minimal value is reduced due to the regenerator dead volume. One can verify that $-W_t/Q_h$ equals the Carnot efficiency $1 - T_k/T_h$ and satisfies the second law $Q_h/T_h + Q_k/T_k = 0$ with exchanged entropy and no irreversible creation.

In Fig. 4, it has been shown that the mole number in the regenerator versus the cycle angle θ is never constant during a transformation. This observation explains why using the expression for work is the good method to calculate the efficiency and why we need computation to find the heat exchange between the gas and the thermostat for the hot, cold and regenerator spaces. In Fig. 5, we have reported the efficiency with and without dead volume considering imperfect regeneration. The efficiency value at $x = 0$ is the Carnot efficiency. In the case of dead volume, the efficiency decreases strongly with the imperfect regeneration. It is surprising to find that with the dead volume in our example, an imperfect regeneration of $x = 0.28$ gives the same efficiency as with no dead volume and $x = 1$ as reported in Fig. 5.

To calculate the efficiency, we start from

$$e = -\frac{W_t}{xQ_{r,1 \rightarrow 3} + Q_{h,\text{cycle}}} \quad \text{with} \quad Q_{h,\text{cycle}} = -\frac{W_t}{1 - \frac{T_k}{T_h}}$$

leading to

$$e = \left(1 - \frac{T_k}{T_h}\right) \frac{1}{1 + x \frac{Q_{r,1 \rightarrow 3}}{-W_t} \left(1 - \frac{T_k}{T_h}\right)}$$

Table 4

Net work, heat released by the regenerator (half cycle) and heat exchange with cooler and heater.

V_r (L)	W_t (kJ)	$Q_{r,1 \rightarrow 3}$ (kJ)	Q_h (kJ)	Q_k (kJ)
0	-80.4	145.4	115.1	-34.7
20	-20.3	134.9	29.0	-8.7

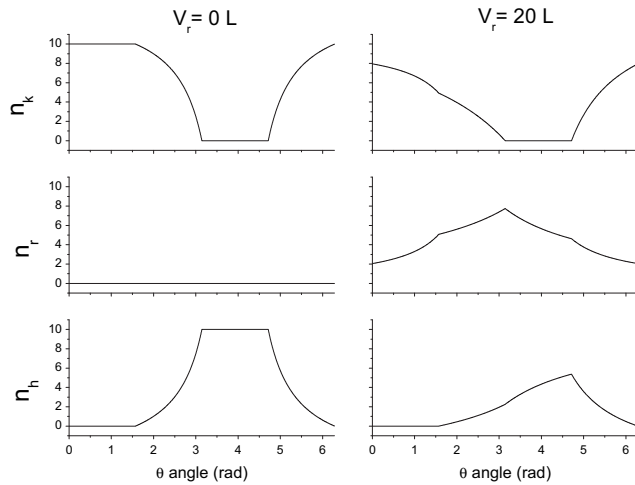


Fig. 4. Variation of the mole number versus the cycle angle θ with and without regenerator volume.

In all cases $-Q_{r,1 \rightarrow 3}/W_t$ increases linearly with dead volume (see Fig. 6 for an example with the input data given in the beginning of the subsection). Consequently, any increase in the dead volume amplifies the effect of the imperfection. Calculation of the linear coefficient dependencies is complicated because of the small variation of $Q_{r,1 \rightarrow 3}$ and the large variation of W . If the dead volume is not taken into account, we have

$$e = \left(1 - \frac{T_k}{T_h}\right) \frac{1}{1 + x(V_r = 0) \frac{Q_{r,1 \rightarrow 3}(V_r = 0)}{-W_t(V_r = 0)} \left(1 - \frac{T_k}{T_h}\right)}$$

and with dead volume

$$e = \left(1 - \frac{T_k}{T_h}\right) \frac{1}{1 + x(V_r) \frac{Q_{r,1 \rightarrow 3}(V_r)}{-W_t(V_r)} \left(1 - \frac{T_k}{T_h}\right)}$$

So the regenerator with dead volume should satisfy the condition

$$x(V_r) \frac{Q_{r,1 \rightarrow 3}(V_r)}{-W_t(V_r)} < x(V_r = 0) \frac{Q_{r,1 \rightarrow 3}(V_r = 0)}{-W_t(V_r = 0)}$$

This condition is of practical importance: the dead volume should be as small as possible. A rough approximation (with an error of less

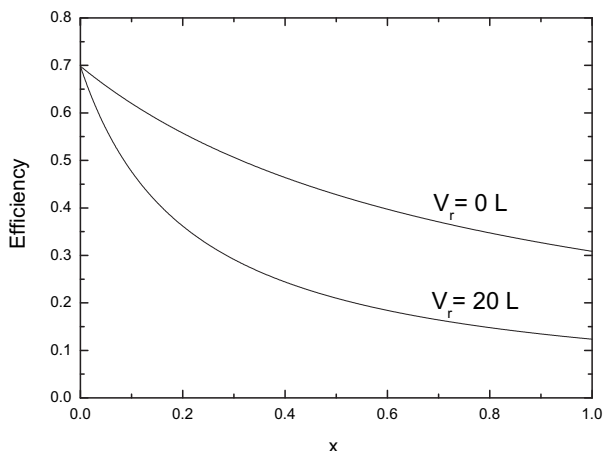


Fig. 5. Efficiency with and without dead volume and imperfect regeneration.

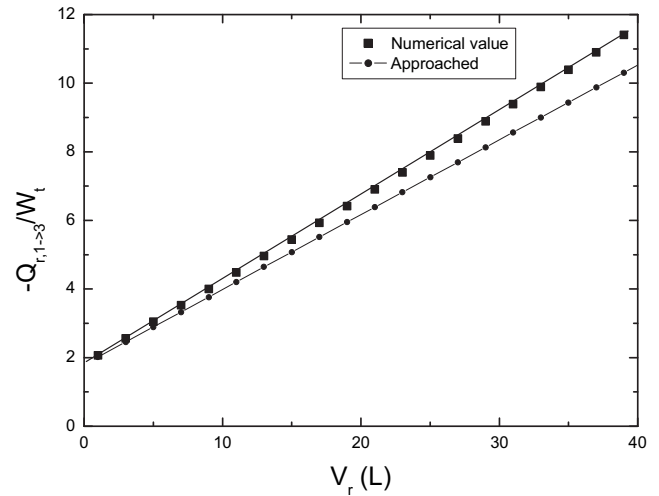


Fig. 6. Effect of the dead volume to the ratio $-Q_{r,1 \rightarrow 3}/W_t$. For the approached formula, we use the correction reported in equation (1).

than 20%) can be made using $W_t(V_r)$ and considering $Q_{r,1 \rightarrow 3}$ to be independent to dead volume, leading to

$$x(V_r) \left(1 + V_r \frac{\frac{T_h + T_k}{T_r} \left(\frac{1}{V_m} - \frac{1}{V_M} \right)}{\log \left(\frac{V_M}{V_m} \right)} \right) \approx x(V_r = 0) \quad (1)$$

This approximation is in good agreement with the numerical values in Fig. 6.

4. Sinusoidal piston motion

A Watt Stirling cycle with sinusoidal piston motion is shown in Fig. 7. The minimum volume V_m and the maximum volume V_M are also denoted. The sinusoidal piston motions used with a dephasing angle of $\pi/2$ (this value is very close to the angle giving the maximum net work) are [11]:

$$V_h = V_{sw} \frac{1}{2} (1 + \cos(\theta))$$

and

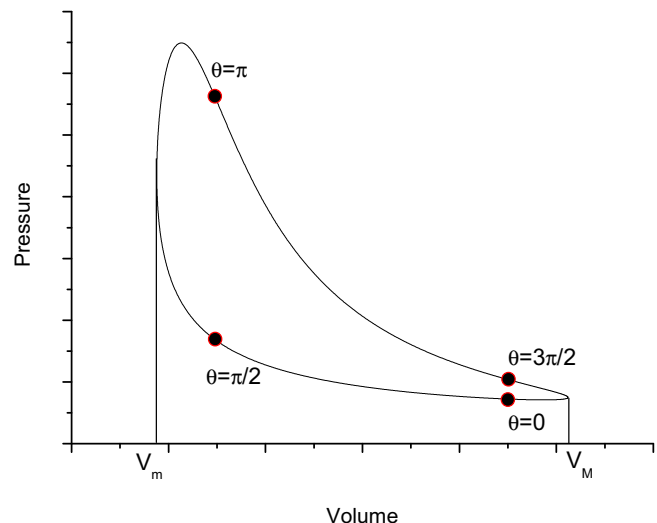


Fig. 7. Watt Stirling cycle with sinusoidal piston motion.

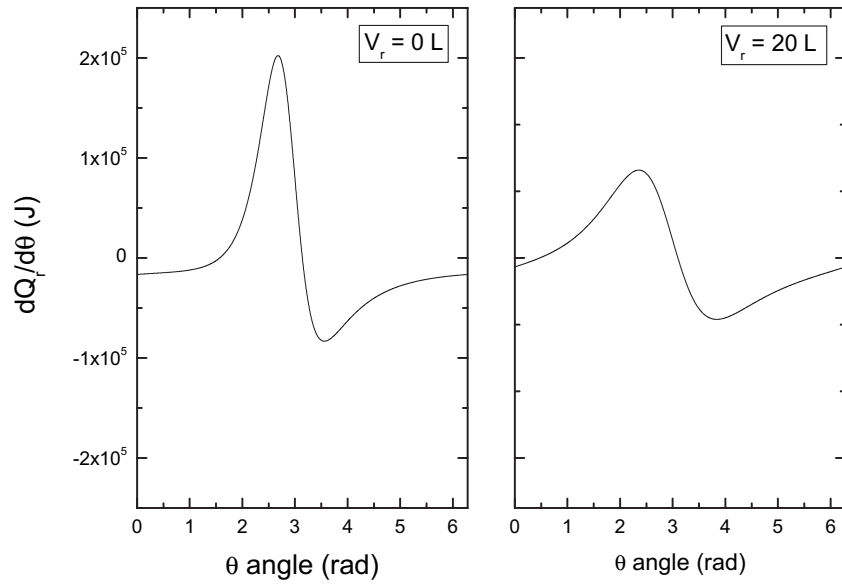


Fig. 8. Heat exchange in the regenerator.

$$V_h = V_{sw} \frac{1}{2} \left(1 + \cos\left(\theta + \frac{\pi}{2}\right) \right) = V_{sw} \frac{1}{2} (1 - \cos(\theta))$$

with θ varying between 0 and 2π and V_{sw} being the swept volume. In this trivial case, the total volume V equals

$$V = V_{sw} \left(1 + \frac{\sqrt{2}}{2} \cos\left(\theta + \frac{\pi}{4}\right) \right)$$

leading to

$$V_m = V_{sw} \left(1 - \frac{\sqrt{2}}{2} \right) \quad \text{and} \quad V_M = V_{sw} \left(1 + \frac{\sqrt{2}}{2} \right)$$

4.1. With or without regenerator dead volume and with perfect regeneration

Using the approach of Berchowitz and Urieli [12], we have

$$W_h = - \int_{\text{cycle}} p dV_h = - \int_0^{2\pi} p \frac{dV_h}{d\theta} d\theta = \frac{\pi}{2} V_{sw} p_{c1} \sin(\beta)$$

and

$$W_k = - \frac{\pi}{2} V_{sw} p_{c1} \cos(\beta)$$

with

$$\beta = \arctan\left(\frac{T_h}{T_k}\right)$$

Table 5

Net work, heat released by the regenerator and heat exchange with cooler and heater.

V_r (L)	W_t (kJ)	$Q_{r,1 \rightarrow 3}$ (kJ)	Q_h (kJ)	Q_k (kJ)
0	-68.0	145.4	97.4	-29.4
20	-17.6	115.5	25.1	-7.6

$$c = \frac{V_{sw}}{2} \sqrt{\frac{1}{T_h^2} + \frac{1}{T_k^2}}$$

$$s = \frac{V_r}{T_r} + \frac{V_{sw}}{2T_h} + \frac{V_{sw}}{2T_k}$$

$$b = \frac{c}{s}$$

and

$$p_{c1} = \frac{2nR}{sb} \left(1 - \frac{1}{\sqrt{1-b^2}} \right)$$

The heat supplied externally is opposed to the work done by the hot piston according to the first law applied over the cycle ($\Delta U = 0 = Q_h + W_h$). The Carnot efficiency is reached as follows:

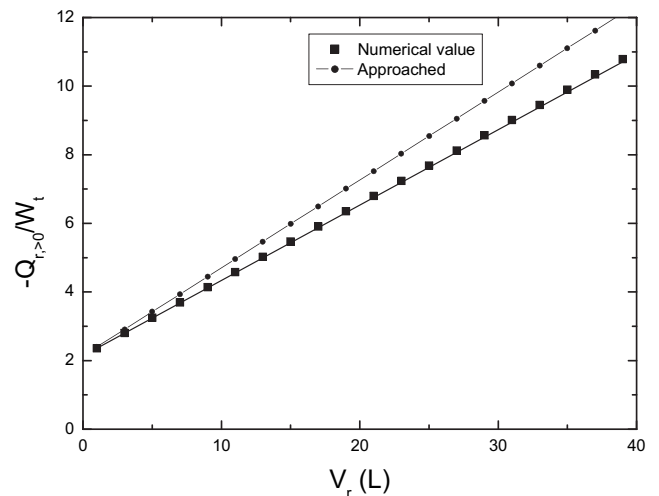


Fig. 9. Effect of the dead volume to the ratio $-Q_{r>0}/W_t$.

$$e = \frac{W_t}{Q_h} = -\frac{W_h - W_k}{-W_h} = 1 - \tan \beta = 1 - \frac{T_k}{T_h}$$

4.2. With or without regenerator dead volume and with imperfect regeneration

In the case without regenerator dead volume, the analysis is identical to the one described above with discontinuous motions of the piston. Even if the regenerator dead volume is taken into consideration, the same numerical approach can be used. The heat exchange in both cases with and without dead volume are presented in Fig. 8.

Table 5 details the energy exchanged during the cycle. With dead volume, the absolute values of the work and the heat exchanged with the hot and cold thermostats are strongly reduced while the heat exchanged by the regenerator is less affected.

We have used the previous result (equation (1)) and plotted a straight line as shown in Fig. 9 corresponding to:

$$-\frac{W_t}{Q_{r>0}}(V_r = 0) \left(1 + V_r \frac{\frac{T_h+T_k}{T_r} \left(\frac{1}{V_m} - \frac{1}{V_M} \right)}{\log \left(\frac{V_M}{V_m} \right)} \right)$$

Even if the complexity of the problem does not allow us to find the exact expression, this linear approximation is an important result of this work. To be efficient, the regenerator should have a dead volume that is as small as possible.

5. Conclusions

A careful analysis has revealed that, in the regenerator with a dead volume, the mole number is not constant during the cycle. With perfect regeneration, Carnot efficiency is reached irrespective of the dead volume but with dead volume, the stored energy in the regenerator is high in comparison with the net work. Without perfect regeneration, the efficiency reduction due to the imperfection is strongly amplified by the dead volume. Using a simple model with standard thermodynamic analysis, we have shown that

a simple expression can be found for characterization of both the imperfection (x) and the dead volume (V_r) in the regenerator given by the formula:

$$x(V_r) \left(1 + V_r \frac{\frac{T_h+T_k}{T_r} \left(\frac{1}{V_m} - \frac{1}{V_M} \right)}{\log \left(\frac{V_M}{V_m} \right)} \right) \approx x(V_r = 0)$$

This formula is a rough approximation that is useful for discontinuous and sinusoidal motions of the pistons.

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